FEM Analisys of the Expandable Intramedullar Nail

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Summary. The paper presents results of numerical analysis of new form of expandable intramedullary nail (patent no. P382247) used in stabilization of proximal femur in adults. The obtained results can be used to optimize geometry of implants as well as mechanical properties of metallic biomaterial they are to be made of.

1 Introduction

Biomechanical quality of a bone - intramedullary nail fixation is important issue of remodeling in nailing osteosynthesis. The biomechanical analysis can be carried out for selected model, construction of the nail and its fastening. On the basis of biomechanical analyses, both geometry and mechanical properties of biomaterial as well as physico-chemical properties can be formed. Biomechanical characteristics of nails enable to compare and select a stabilization method for individual patients.

Nowadays, elastic methods of osteosynthesis are promoted. The basic aim of these methods is assuring micromovements of bone fragments that stimulate remodeling of bone by differentiation of its structure. Strains in bone tissue in the elastic range generate electromechanical potentials in bone. Therefore, establishing the optimal axial, transverse and torsional stiffness is crucial.

Determination of stresses and strains in intramedullary osteosynthesis can be applied in selection of mechanical properties of nails biomaterial and in forming of structure and physio-chemical properties of surface as well. Biocompatibility of implants is considered with reference to metabolic, bacteriological, immunological and oncogenic processes. It is connected with individual reactivity of implants' user. Therefore, biomaterials of even identical mechanical properties but diverse physio-chemical properties of surface should be differentiated [1]–[8].

2 Materials and Methods

Numerical model of femur, worked out in Laboratiorio di Technologia dei Materiali, Instituti Ortopedici Rizzoli, was applied in the biomechanical analysis of the expandable intramedullar nail. Young's modulus E=18600 MPa and Poisson's ratio v=0.3 were assumed for femur model.

E. Pietka and J. Kawa (Eds.): Information Tech. in Biomedicine, ASC 47, pp. 537–544, 2008.
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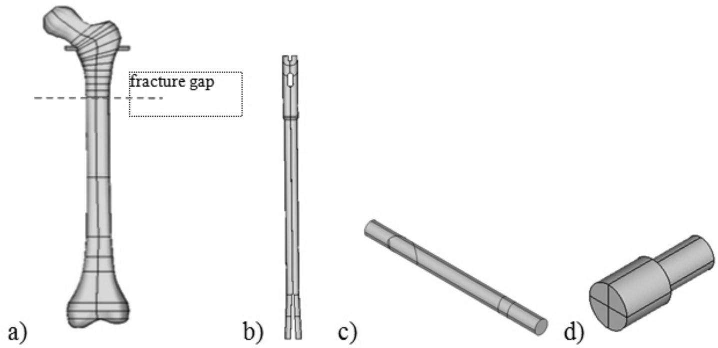

Fig. 1. Geomtrical model of the femur – expandable intramedullary nail system: a) view of the system, b) expandable intramedullary nail, c) lock, d) blocking screw

Geometrical model of expandable intramedullar nail was prepared in ANSYS. The following mechanical properties were selected:

- Stainless steel Cr-Ni-Mo: $E=2 \cdot 10^5$ MPa, Poisson's ratio $\nu=0.33$
- Ti-6Al-4V alloy: $E=1.1 \cdot 10^5$ MPa, Poisson's ratio $\nu=0.33$.

Geometrical model of the analyzed femur - expandable intramedullary nail system was presented in Fig. 1. The analysis was carried out for proximal simple fracture (100 mm below trochanter) – Fig. 1. On the basis of the geometrical models a finite element mesh was generated – fig. 2a. The meshing was realized with the use of the SOLID95 element – Fig. 2b. This type of element is used for the three-dimensional modeling of solid structures. The element is defined

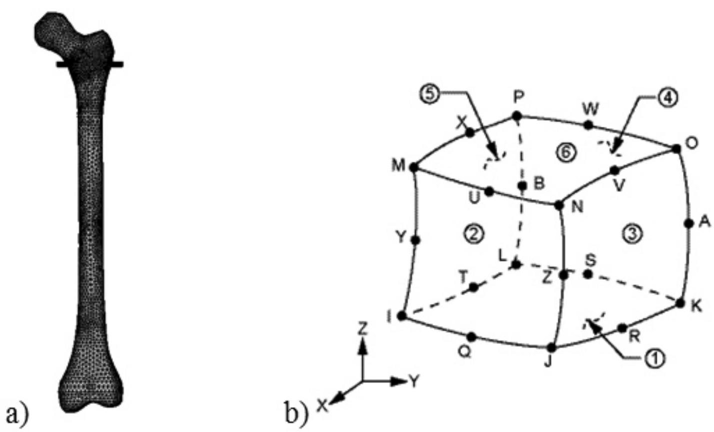

Fig. 2. a) Discrete model of the femur – expandable intramedullary nail system, b) The SOLID 95 finite element

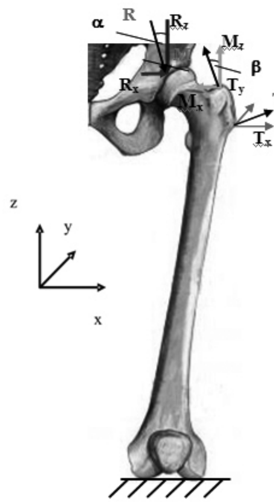

Fig. 3. Loading scheme of model

by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions.

In the course of the work, displacements, strains and stresses, depending on the assumed mechanical properties, were calculated. In order to carry out the calculations, appropriate initial and boundary conditions reflecting phenomena in real system were determined. The following assumptions were set:

- lower part of the femur was immobilized (all degrees of freedom of nodes on external surfaces of condyles were taken away),
- proximal part of femur was loaded according to the scheme presented in fig. 3. The applied loading was presented in table 1.

The first stage of the analysis was determination of displacements, strains and stresses:

- in healthy femur,
- in elements of the femur – expandable intramedullary nail made of stainless steel,
- in elements of the femur – expandable intramedullary nail made of Ti-6Al-4V alloy.

Table 1. Forces applied to the femur [1]

Forces, N								
R			M			T		
x	y	z	x	y	z	x	y	z
494	-1824	0	-494	1208	0	-54	-21	0

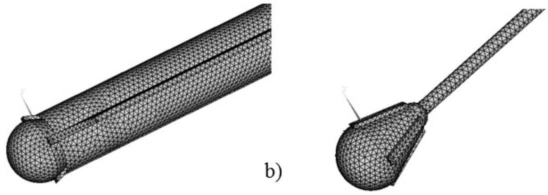

Fig. 4. Numerical model of the expandable part of the intramedullary nail – a) and expander – b) after discretization with SOLID 95 finite element

The obtained stresses and strains were reduced values according to the Huber-Misses-Henck hypothesis.

The second stage of the work was analysis of the nail during expansion. Axial displacement of the expander from 3 mm (contact with expandable end of the nail) to 7 mm with increment equal to 1 mm was analyzed. In order to carry out the analysis geometrical model of the expander and the expandable end of the nail were discretized by SOLID 95 element – Fig. 4.

Calculations were carried out in ANSYS 11 with the use of PC of the following parameters: Procesor Intel Core 2 Duo E6600, 4 GB RAM, Windows Vista Ultimate 64 bit.

3 Results

3.1 Results of the Femur – Expandable Intramedullary Nail System Analysis

The maximum obtained values of displacements, strains and stresses for all analyzed variants were presented in table 2 and Fig. 5, 6, 7.

Table 2. Results of the FEM analysis of the femur – intramedullary nail system

	Displacement. mm				Strains ε. %				Strains σ. MPa			
	x	y	z	Σ	x	y	z	Σ	x	y	z	Σ
Femur												
Femur	-15.8	0.5	1.8	16.2	10	3	19	54	222	148	452	635
Femur – expandable intramedullar nail system (Cr-Ni-Mo steel)												
Femur	-16.5	0.4	3.2	17.0	19	7	13	38	589	281	404	706
Nail	-14.1	0.3	3.2	14.1	2	2	9	18	2014	2030	4594	2899
System	-16.5	0.4	3.2	17.0	19	7	21	38	2680	2920	5713	4332
Femur – eexpandable intramedullar nail system (Ti-6Al-4V alloy)												
Femur	-20.4	0.8	4.2	21.1	18	8	13	46	475	303	471	866
Nail	-17.3	0.6	4.2	17.3	4	2	16	29	1765	1210	2708	2844
System	-20.4	0.8	4.2	21.1	18	8	37	46	2714	2818	5670	3938

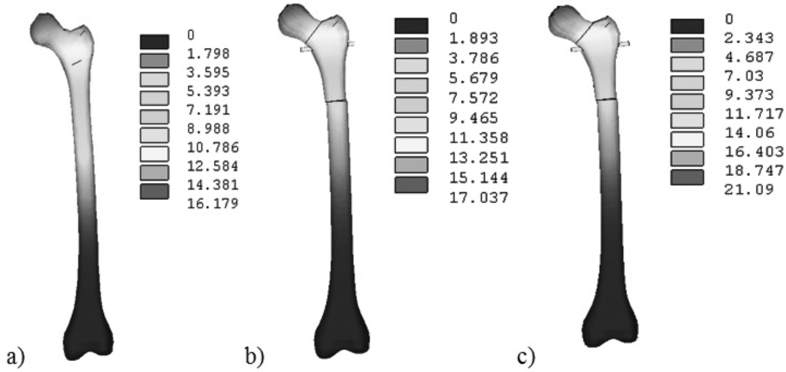

Fig. 5. Displacement vector sum, mm a) femur, b) femur – intramedullary nail system (Cr-Ni-Mo), c) femur – intramedullary nail system (Ti-6Al-4V)

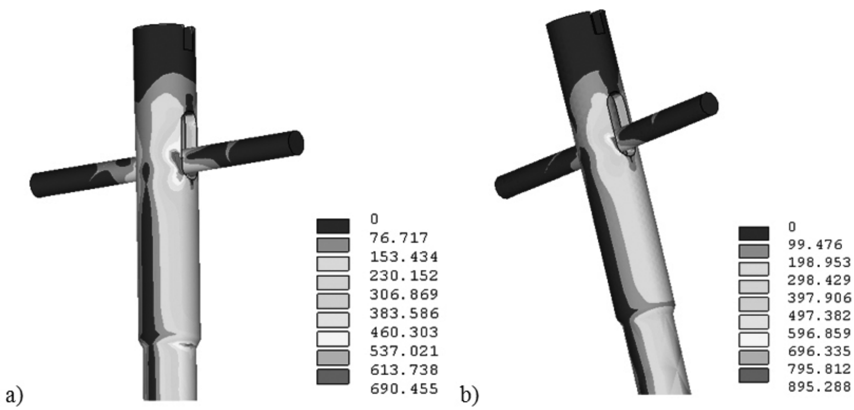

Fig. 6. Stress distribution in the nail, MPa: a) (Cr-Ni-Mo) nail, c) (Ti-6Al-4V) nail

The analysis showed no significant differences in displacements of the head for the healthy bone and the bone with the implanted nail. For the system with the nail made of stainless steel, the displacement of femoral head was equal to 17.0 mm. However, for the system with the nail made of titanium alloy, the displacement was equal to 21.1 mm. This indicates stiffness comparability of the healthy bone to the bone with the implanted nail – Fig. 5.

Maximum reduced stresses were localized in the area of contact between the lock and the nail. In the contact point the maximum value was equal to 4332 MPa for the stainless steel and 3938 MPa for the titanium alloy. But the analysis of the whole nail indicates that stresses did not exceed 690 MPa for the steel and 895 MPa for the titanium alloy – Fig. 6.

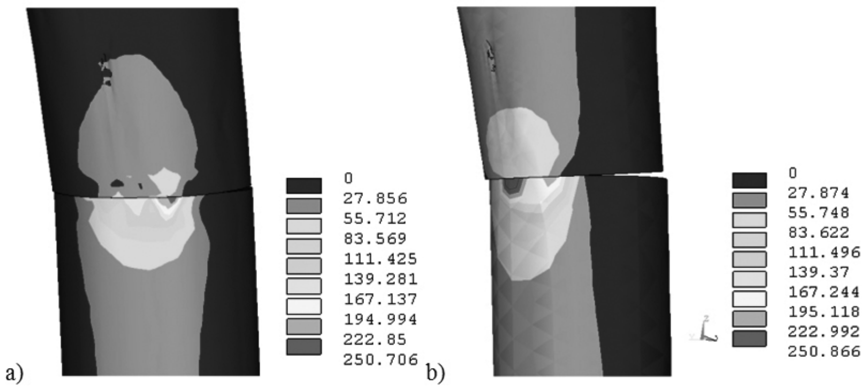

Fig. 7. Stress distribution in the fracture gap, MPa: a) (Cr-Ni-Mo) nail, c) (Ti-6Al-4V) nail

Also stresses in the fracture gap only locally exceeded the allowable value (250 MPa). Exceeding of the value causes damage of bone tissue. Maximum stresses are localized in the area of contact between the bone and the lock. On the basis of clinical research it was affirmed that bone is characterized by visco-elastic properties which allow to adapt tissues to existing loading without damage.

3.2 Results of the Expansion of the Intramedullary Nail Analysis

In the result of calculations, displacements, strains and reduced stresses were determined. Furthermore, characteristics of the expander and the expanding part of the intramedullary nail were also worked out – Table 3 and Fig. 8 and Fig. 9.

Table 3. Results of the FEM analysis of the expandable intramedullary nail expansion

	Axial displacement of the expander				
	3	4	5	6	7
Cr-Ni-Mo steel					
Displacement of expandable end of nail r. mm	0.52	1.03	1.50	2.02	2.48
Strains ε. %	0.18	0.36	0.53	0.71	0.82
Stresses σ. MPa	365	722	1039	1408	1721
Ti-6Al-4V alloy					
Displacement of expandable end of nail r. mm	0.52	1.03	1.50	2.02	2.48
Strains ε. %	0.18	0.36	0.53	0.71	0.82
Stresses σ. MPa	199	397	571	774	946

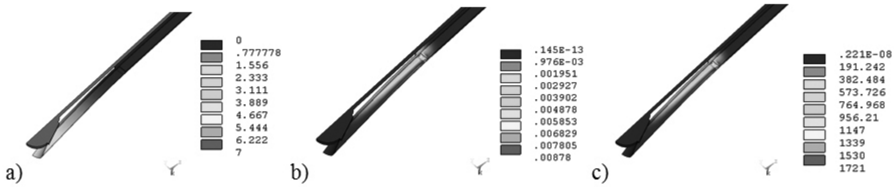

Fig. 8. Results of the analysis for the expander's dispacement equal to 7 mm for the mail made of stainless steel: a) displacements of the expander and the expandable end, mm, b) reduced strains in the expandable end, x100%, c) reduced stresses in the expandable end, MPa

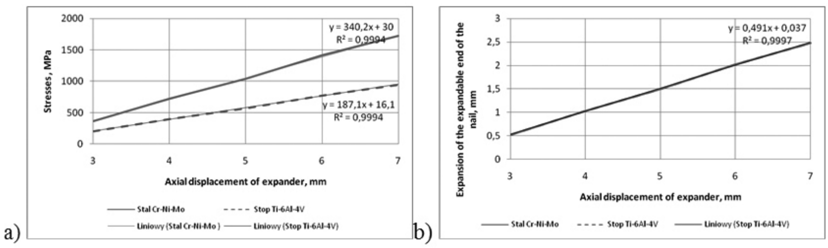

Fig. 9. a) stresses in the expandable end in a function of axial displacements of the expander, b) expansion of the expanding end in a function of axial displacements of the expander

The analysis showed that axial displacement of the expander is accompanied by linear increase of strains and reduced stresses up to maximum values. For the axial displacement equal to 7 mm maximum stresses for the steel are equal to $\sigma = 1721$ MPa and for the Ti-6Al-4V alloy σ=946 MPa – Fig. 8a, b, c and Fig. 9a.

Independently on the applied biomaterial, the expansion of the end was the same and increased linearly depending on the axial displacement of the expander, reaching the maximum value r=2.48 mm – Fig. 9b.

4 Conclusion

The numerical analysis was carried out in order to calculate displacements, strains and stresses in the expandable intramedullary nail used in stabilization of proximal femur in adults. The obtained results are important for selection of mechanical properties of metallic biomaterials intended for this type of implants. On the basis of the established boundary conditions and obtained results one can conclude that:

- maximum reduced stresses were localized in the area of contact between the lock and the nail. In the contact point the maximum value was equal to

4332 MPa for the stainless steel and 3938 MPa for the titanium alloy. But the analysis of the whole nail indicates that stresses did not exceed 690 MPa for the steel and 895 MPa for the titanium alloy,

- also stresses in the fracture gap, contact area of the bone fragments as well as in the whole bone did not exceed the allowable value of 250 MPa. Exceeding of the value causes damage of bone tissue,
- the analysis showed no significant differences in displacements of the head for the healthy bone and the bone with the implanted nail. For the system with the nail made of stainless steel, the displacement of femoral head was equal to 17.0 mm. However, for the system with the nail made of titanium alloy, the displacement was equal to 21.1 mm. This indicates stiffness comparability of the healthy bone to the bone with the implanted nail,
- for the proposed geometry of the nail the allowable expansion of the expandable end was equal to 1.03 mm for the stainless steel (axial displacement of the expander was equal to 4 mm) and 2.48 mm for the titanium alloy (axial displacement of the expander was equal to 7 mm).

Acknowledgement. The work was realized within the confines of the research project MNiSzW Nr R08 016 01 funded by the Minister of Science and Information Society Technologies.

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